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METEOROLOGICAL PHENOMENA ASSOCIATED WITH RAPID IRREGULAR CHANGES IN THE LENGTH OF THE DAY

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by

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Abstract

The use of modern techniques has revealed significant short-period fluctuations (around five to ten days) in the length of the day due largely to the transfer of angular momentum between the solid earth and the atmosphere. An attempt has been made in this paper to correlate these irregular changes, with atmospheric dynamics, as revealed by certain meteorological phenomena such as cloud patterns and pressure fields in the Northern Hemisphere. Typical pressure fields over North America are shown and a hemispherical estimate of the mountain torque due to pressure differences between the east and west faces of large mountain areas is given.

These investigations reveal a close relationship between the torque required to produce the changes in the length of day and the mountain torque over the Northern Hemisphere. There is some indication that variations in the mountain torques of Northern Asia, Europe, and Africa are more significant than those of North America and Southern Asia.

1. Introduction

The zonal motion of the atmosphere relative to the underlying solid Earth is on average westerly and the excess angular momentum $M_a = I_a \Delta\Omega$ associated with that motion (where I_a is the moment of inertia of the atmosphere about the Earth's rotation axis and $\Delta\Omega$ the angular velocity of the atmosphere relative to the Earth) is about 10^{-8} times the angular momentum of the whole Earth. The total excess angular momentum of the atmosphere due to its super-rotation is equivalent to a change of 2×10^{-3}s of the Earth's rotation period. Fluctuations of between 1/10 and 1/5 of this are observed and are generally ascribed to meteorological causes, implying that $\Delta\Omega$ is subject to considerable irregular variations (up to 20%) which any successful theoretical "budget calculations" of the atmosphere must account for correctly. In order to do so the model must be able to represent (a) the torques at the Earth's surface that bring about the observed angular momentum transfer between the atmosphere and the solid Earth and (b) the motions that bring about the consequential redistribution of zonal flow (mainly the position of the mean tropospheric jets). Needless to say, the meteorological observations are insufficiently accurate and abundant to enable complete angular momentum "budget calculations" to be made and numerical models of the atmosphere are too crude at present to deal with this problem in more than general terms.

Recent improvements in methods for monitoring the Earth's rotation (see below) provide a stimulus for considering what meteorological use can be made of these new data, even though it will be impossible to make full use of them for many years to come when good global meteorological coverage becomes available. It would, however, seem reasonable to investigate whether or not the more pronounced l.o.d. changes are associated with any distinct changes in circulation pattern, particularly in those regions of the Earth's surface where the interaction between atmospheric motions and irregular topography might contribute significantly to the fluctuating torque coupling the atmosphere to the solid Earth.

Sections 2 and 3 are reviews of l.o.d. observations and mountain torques respectively. An outline of a preliminary investigation of the association of certain meteorological phenomena with l.o.d. changes is given in section 4. The cloud patterns

were of limited success but the pressure patterns and torque appeared to be rather more useful and would warrant further studies. This work links up some of the l.o.d. studies (e.g. Lambeck and Cazenave (1973, 1974), Okazaki (1975)) with the investigations of mountain torque (e.g. Newton (1971), Oort and Bowman (1974)).

2. Length of day observations

The l.o.d. is measured by timing the meridional transits of selected storms over 24 hours to give the Universal Time (UT) and comparing this with a standard time scale which is currently the International Atomic Time (IAT). The difference between UT and IAT gives the excess l.o.d, and changes in UT-IAT gives the change in l.o.d. as these changes are very small the difference must presently accumulate over a minimum of five days for it to be clearly observed above the noise levels. Before the mid 1950's when atomic time was introduced an integration over a much longer period was required.

A plot of the excess l.o.d. against time reveals a number of long term seasonal variations, the largest of these being the annual term, first reliably reported by Stoyko (1936). Later the semi-annual term (Smith & Tucker (1953)), monthly and fortnightly terms (Markowitz (1955)) were discovered, all having their origins in tidal excitations. These changes are superimposed on the decade and longer period trends of a few milliseconds due to angular momentum transfer between the Earth's mantle and liquid.core (for recent discussion and references see Hide (1977)). A comprehensive review of early work on the subject has been given by Munk and MacDonald (1960).

With the advent of atomic time and more accurate techniques for monitoring the Earth's rotation (O'Hara (1975)) rapid irregular fluctuations in the l.o.d., reaching a maximum about half a millisecond occurring on time scales upwards of a few days were discovered. These are best studied by looking at UT2, Universal Time with polar motion and seasonal terms removed, which can be found in the Bureau Internationale de l'Heure B.I.H. Annual Reports.

The excess l.o.d. is plotted in figure 2.1, which was originally obtained by Morrison (1974) by differencing the smoothed values of UT2 - IAT at ten day intervals. These irregular changes and the more regular seasonal variations are thought to be due to exchange of angular momentum between the solid Earth and the atmosphere (March &

Miller (1950), Lambeck and Cazenave (1973) and (1974), Okazaki (1975)).

When our techniques for monitoring the l.o.d. (see Rochester (1973)) become standard practice the daily values will be resolved and indications of whether these irregular fluctuations in l.o.d. are smooth or discontinuous will be given, facilitating a greater understanding of the processes involved. These new techniques include laser ranging of satellites and the Moon, using corner cube reflectors, and very long baseline interferometry.

The periods of pronounced rapid l.o.d. change used in this paper were obtained from the smoothed data of UT2-IAT by selecting occasions when this changed by a millisecond or more between successive five day values, equivalent to a change in l.o.d. of 0.2 ms or more. These occasions and the magnitude of the l.o.d. change are indicated in table 2.1. The corresponding features are clearly visible in figure 2.1 although the two are not exactly equivalent due to the different time intervals used. As can be seen from this table the sharp changes take place most commonly over periods of ten days with a few over periods of five and fifteen days. Smaller magnitude changes do sometimes occur over longer periods but these are beyond the scope of the present work.

3. Mountain Torques

In order to satisfy the conservation laws during the irregular l.o.d. changes described in the previous section angular momentum must be transferred between the solid Earth and the atmosphere as only atmospheric angular momentum can be conceived to change rapidly enough. The consequent torque Υ applied at the Earth's surface is equal to the rate of change of angular momentum given by

$$\Upsilon = I \frac{\partial \omega}{\partial t} + \omega \frac{\partial I}{\partial t} \qquad (3.1)$$

where ω is the angular velocity of the Earth and I its Moment of Inertia which for these purposes, ignoring earthquakes, can be considered constant giving

$$\Upsilon = I \frac{\partial \omega}{\partial t} \qquad (3.2)$$

This torque is the difference between the easterly and westerly frictional and mountain torques (the latter first suggested by Starr (1948)), and mainly due to pressure differences on these scales considered here (see Mason & Sykes 1977), which

is zero in the mean but must fluctuate considerably during periods of very pronounced l.o.d. change. Equation 3.2 shows that for a typical large change in l.o.d. of 0.2 ms in five days, (or 1.7×10^{-13} rads s^{-1} in angular velocity) a torque of 30×10^{18} kg m^2 s^{-2} is required. The consequent change of total angular momentum of the atmosphere is around 10-15%. The eastward mountain torque at latitude is related to the geopotentials Z_E and Z_W to the east and west of mountains by the equation

$$\tau(\phi) = \int_{p_T}^{p_o} \sum (Z_E - Z_W)\, a \cos\phi \, dp \qquad (3.3)$$

(see appendix) where a is the radius of the Earth, p_T and p_o the pressures at the top and bottom of the mountain and $\sum$ the sum over all mountains in the latitude belt. Using these principles a number of calculations of mountain torques have been attempted, the first by White (1949) who calculated the mountain torque for latitudes 25-65N. It was not until recently, however, that sufficient climatological data has been accumulated for a global analysis of this quantity to be completed. Newton (1971) was able to evaluate the mid-season monthly mean torques over the numerous mountain ranges and latitudes of the Earth using these data. A recent detailed study over a limited latitude range is that of Oort and Bowman (1974) who calculated, for the period 1958-1963, the mountain torque as monthly and annual mean values. They showed that the monthly mean mountain torques fluctuated by as much as 16×10^{18} kg m^2 s^{-2} from one year to the next and by as much as 20×10^{18} kg m^2 s^{-2} from one month to the next. The average standard deviation for the months October to February was 5.2×10^{18} kg m^2 s^{-2} showing that the fluctuations in the mountain torque are large and variable and are of the right order of magnitude required to produce the l.o.d. changes. Over the shorter periods considered here the torque is probably greater suggesting that large scale atmospheric flow patterns in the vicinity of large mountain complexes may show changes which can be associated with those of the l.o.d. Meteorological phenomena to be examined in this report depended on the availability of data and hence cloud photographs and pressure data during selected periods of l.o.d. variation were investigated.

4. Association of Meteorological Phenomena with l.o.d. changes

(i) Cloud patterns

As the Rockies and Andes are sites where the Earth exerts a strong torque on the atmosphere it was decided to study the cloud patterns over these mountains to see if they gave any indication of this interaction during periods of rapid l.o.d. change. For this study satellite infrared and visible photographs obtained during 1968 to 1974 were used.

The principal difficulty was found to be the great variability of cloud patterns and no consistent relationship was found, although, certain interesting features were apparent during some of the periods shown in table 2.1. In December 1973 the cloud patterns indicated that a continuous stream of depressions were incident on the west coast of North America between 35N and Alaska. These could have set up a strong westerly flow over the Rockies, possibly producing the forcing which would have had the effect of decreasing the l.o.d.. This was followed in early January 1974 by a period with no depressions reaching America and hence probably lighter winds. During this period there was an increase in l.o.d. suggesting that in these two months there was some degree of correlation between cloud patterns and l.o.d. fluctuations.

Two unusual features were visible in April 1968, one over the Rockies and the other over the Andes. On the 11th, 12th and 13th the normal clouds over the Peruvian Current disappeared due possibly to increased winds or a reversal of flow, whereas on the 11th over the Rockies between 15 and 35 N there was a marked cloud band. It is not easy to say whether or not these features could be related to an increase or decrease in the l.o.d., however, Lambeck and Cazenave (1974) were able to explain the l.o.d. changes for this period by the propagation southwards and ultimate breakdown of strong westerlies in the Northern Hemisphere. As already mentioned the variability of cloud patterns is probably the main reason for the failure to find a clear relationship but others include the limited latitudinal extent of some of the photographs (only to 50N in some cases) and because other regions of the world may be more significant.

(ii) Pressure fields

As the pressure difference across mountain ranges can produce a significant torque on the atmosphere it was decided to study the fields of pressure and the geopotentials associated with the l.o.d. changes, with particular reference to data in the vicinity of the Rockies. Half-monthly normals and pentad means of surface pressure and 500 mb. Geopotentials were accessed from the climatological data banks. These data are only available for the Northern Hemisphere and are presented on a grid at every 5 degrees of latitude and 10 degrees of longitude. The pentad data were subtracted from the relevant half-monthly normals so that the anomalies could be studied.

These surface pressure anomalies appeared to bear some relationship to periods of rapid decrease in l.o.d., two distinct features being evident. First there was a low pressure anomaly to the east of the Rockies and second there was usually a high pressure anomaly to the west, both extending over at least 30 degrees of latitude. Even when the latter did not exist the anomaly to the west was higher than that to the east indicating that a strong westerly torque was applied to the atmosphere. Typical patterns are given in figures 5.1 and 5.2 which show the land over 500 metres and the anomalous pressure at the grid points. In these two cases the anomalous pressure difference between the west coast and east face of the Rockies at 40N is as much as 6 mb and 9 mb respectively, enough to produce a substantial torque.

During periods of rapid increase in l.o.d. the surface pressure anomalies did not reveal such a clear pattern, indeed, in many cases a torque of the wrong sign was indicated. The most common feature was a high anomaly to the north west of the Rockies with often a low to the south or east as in figure 5.3, although, this was sometimes reversed. It therefore appears that on occasions when the Earth is speeding up i.e. l.o.d. decreasing, the surface pressure fields over the Rockies fit a particular pattern such that the mountains exert a strong influence on the circulation, but when the Earth is slowing down other ranges appear to be more significant.

Having established the possibility of a relationship between the mountain torque in the Northern Hemisphere and the l.o.d. a quantitative analysis was attempted for January 1972 (see Appendix). Five day means of geopotential height were computed on the 1977 point National Meteorological Center grid. This enabled the use of greater resolution and more levels than available with the previous pentad data. The results given in table 5.1 present the mountain torque as a function of altitude and location. Comparing these values with the mean January figures obtained by Newton (1971) there are a number of significant differences. Although the positive torque over N. America is considerably less during this period (2.2×10^{18} kg m^2 s^{-2} compared with 8×10^{18} kg m^2 s^{-2}) producing an effect opposite to the l.o.d. indications, this is more than compensated by an increase in torque over the rest of the Northern Hemisphere. In each region the eastward torque is larger than the mean for January by between 5 and 9×10^{18} kg m^2 s^{-2}, with the result that over the whole area considered the total mountain torque was 22.6×10^{18} kg m^2 s^{-2} compared with a torque of 24×10^{18} kg m^2 s^{-2} required for the l.o.d. change of 0.16 ms. for this period, a surprisingly close agreement, indicating that the Northern Hemisphere is perhaps the main source of the l.o.d. fluctuations. Further evidence supporting this view is obtained from the time of year of the large changes. These always occur in the northern winter or early spring when the circulation is most active in the Northern Hemisphere.

The mountain torque as a function of latitude and pressure level is shown in table 5.2, where the 1000 mb level covers an interval of 37.5 mb and the others an interval of 50 mb. It can be seen that in this case the lowest three levels, namely those at 1000 mb, 950 mb, and 900 mb, were most significant, together producing a torque of 23.2×10^{18} kg m^2 s^{-2}. Comparing these results with those of Oort and Bowman (1974) these are the levels where the main differences occur. Of course further case studies are needed but it may be that only the lowest levels of the atmosphere need be considered as the higher levels only contribute a second order correction to the torques. It is also noteworthy that the latitudes with the highest mountains do not necessarily produce the largest torque, in fact at 35N it is particularly small.

5. Concluding remarks

As Southern Hemisphere data at 1000, 850 and 700 mbs are not available at the Met Office a comparison between global mountain torque and the l.o.d. changes is not possible; however, as most of the large mountain complexes are in the Northern Hemisphere and the large l.o.d. changes take place during the Northern winter and early spring when Southern Hemisphere circulations are rather slack, the major contributions have probably been accounted for.

Although very little use could be made of the cloud patterns, there appears to be a distinct association of the irregular l.o.d. change and the mountain torque, at least during the selected period when data were available. Since the mountain torque is of the same size as that required for the l.o.d. change it appears that the torque produced by irregular topography may be sufficient by itself, excluding frictional torque, to cause most of the irregular pattern in the l.o.d. profile. The importance of the interaction of the atmosphere with topography must be emphasized and further investigations of some of these phenomena are well merited, particularly when meteorological coverage improves and the new techniques for monitoring the Earth's rotation are established. Further opportunities to study these phenomena should arise when analysis of the data from the First GARP Global Experiment (FGGE) is attempted.

Appendix

From the equation for local rate of change of absolute angular momentum the mountain torque τ can be written

$$\tau = \int a \cos\phi \, \frac{\partial p}{\partial x} \, dV \quad , \tag{1}$$

positive torques being those which produce an acceleration of the atmosphere in the eastward direction. a is the radius of the Earth, ϕ the latitude, p the pressure and V a volume. The torque $\tau(\phi)$ at any latitude is thus

$$\tau(\phi) = \int_0^z \int_{x_E}^{x_W} a \cos\phi \, \frac{\partial p}{\partial x} \, dx \, dz \tag{2}$$

As data are normally in the form of geopotentials Z rather than pressure equ. 2. can be rewritten

$$\tau(\phi) = -\int_{p_0}^{p_\tau} \int_0^{2\pi} a \cos\phi \, \frac{\partial z}{\partial \lambda} \, d\lambda \, dp \tag{3}$$

where p_τ and p_0 are the pressures at the top and bottom of the mountain range and λ the longitude. For calculations this is evaluated over individual ranges so that the integral becomes a summation over each range, i.e.

$$\tau(\phi) = \int_{p_\tau}^{p_0} \sum_i (z_E - z_W) \, a \cos\phi \, dp \tag{4}$$

where E and W refer to east and west.

In this paper five day geopotential means were computed for the 1000 mb, 850 mb, 700 mb, and 500 mb levels and the analysis was performed at 50 mb intervals between these levels, the geopotentials between the standard levels being determined by linear interpolation. The latitudinal resolution was five degrees from the pole to 40N and from 25N to 15N but between these it was 2.5 degrees since the topography is more complex in this region. As only data on a synoptic scale were available the relief was smoothed and only features covering at least two degrees of longitude were retained.

Thus using equation (4) the fields of the geopotentials and the modified topography, the mountain torque over each pressure belt and mountain range was calculated. These results are presented in tables 5.1 and 5.2.

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Legends for diagrams

Figure 2.1

Irregular fluctuations in the excess length of day compared with the atomic day of 86400 seconds obtained from differenced 10 day values of IAT-UT2. The periodic seasonal variations shown in the caption have been removed from the data and the main areas of the plot considered are indicated by A, B, and C.

Figure 5.1

Pressure anomalies over North America in mbs for Dec 7-11 1971 during a length of day decrease. Pressure contours are at 5 mb intervals (——— positive anomaly, ----- negative anomaly) and the 500 metre contour indicates the approximate extent of the Rockies.

Figure 5.2

Pressure anomalies over North America in mbs for Dec 22-26 1973 during a length of day decrease. Contours are as for figure 5.1.

Figure 5.3

Pressure anomalies over North America in mbs for Mar 17-21 1971 during a length of day increase. Contours are as for figure 5.1.

Table 2.1 Selected periods between 1968 and 1974 of rapid irregular l.o.d. changes obtained from differenced 5 day values of IAT - UT2.

Period	Change in l.o.d. (ms)
9-14 Mar 1968	- 0.22
3- 8 Apr 1968	0.42
8-13 Apr 1968	0.60
13-18 Apr 1968	- 0.18
18-23 Apr 1968	- 0.44
14-19 Mar 1971	0.18
19-24 Mar 1971	0.24
24-29 Mar 1971	0.18
29 Mar-3 Apr 1971	- 0.46
4- 9 Dec 1971	- 0.22
9-14 Dec 1971	- 0.18
29 Dec-3 Jan 1971-72	0.16

Period	Change in l.o.d. (ms)
3- 8 Jan 1972	0.16
8-13 Jan 1972	0.18
23-28 Dec 1973	- 0.22
28 Dec-2 Jan 1973-74	- 0.44
2- 7 Jan 1974	0.28
7-12 Jan 1974	0.38
17-22 Jan 1974	- 0.44
27 Jan.-1 Feb 1974	0.36
1- 6 Feb 1974	0.20
12-17 Apr 1974	0.24
17-22 Apr 1974	0.26

Table 5.1 Computed mountain torque in units of 10^{18} kg m^2 s^{-2} per 5 latitude belt, using 50 mb intervals, for the period 3-7 January 1972.

Latitude	Asia N. of 37.5	Asia S. of 37.5	Europe Africa and Arabia	Rockies	Greenland	Total for Lat. belt
80					0.4	0.4
75					3.5	3.5
70					4.6	4.6
65	- 1.0		0.9	1.3	1.3	2.5
60	0.5		0.6	2.4		3.5
55	- 1.6			0.0		- 1.6
50	0.8		1.2	- 4.1		- 2.1
45	- 1.5		1.7	- 5.5		- 5.3
40	1.3		1.2	- 4.5		- 2.0
35		2.0	0.9	- 2.0		0.9
30		2.1	0.7	0.9		3.7
25		3.3	1.4	1.5		6.2
20		1.1	1.2	1.5		3.8
15		0.7	2.9	0.9		4.5
15-80	- 1.5	9.2	12.7	- 7.6	9.8	22.6

Table 5.2 Computed mountain torque in units of 10^{18} kg m^2 s^{-2} per 5 degree latitude belt as a function of latitude and height for the period 3-7 January 1972.

Latitude	1000 mb	950 mb	900 mb	850 mb	800 mb	750 mb	700 mb	650 mb	600 mb	550 mb	500 mb
80	0.1	0.1	0.1	0.1	0.1						
75	0.4	0.5	0.5	0.6	0.6	0.6	0.3				
70	0.5	0.7	0.7	0.8	0.7	0.7	0.7				
65	0.7	1.0	0.7	- 0.1	0.0	0.1	0.1				
60	1.0	1.2	0.9	0.2	0.2						
55	0.5	0.0	- 0.6	- 1.0	- 0.5						
50	0.2	- 0.2	- 0.5	- 0.4	- 0.7	- 0.6	- 0.2				
45	- 0.7	- 0.5	- 0.8	- 1.1	- 0.9	- 0.6	- 0.6				
40	0.3	0.1	- 0.2	- 0.5	- 0.2	- 0.8	- 0.7	- 0.1			
35	1.0	0.9	0.3	0.0	- 0.2	- 0.1	- 0.3	- 0.2	- 0.1	- 0.2	- 0.2
30	1.4	1.2	1.0	0.8	0.5	0.1	- 0.2	- 0.2	- 0.3	- 0.3	- 0.3
25	1.8	1.6	1.3	1.1	0.5	0.1					
20	1.2	1.3	0.8	0.3	0.2						
15	1.9	1.7	0.7	0.1	0.1						
Total	9.4	9.0	4.4	0.2	0.4	- 0.5	- 0.8	- 0.5	- 0.4	- 0.5	- 0.5

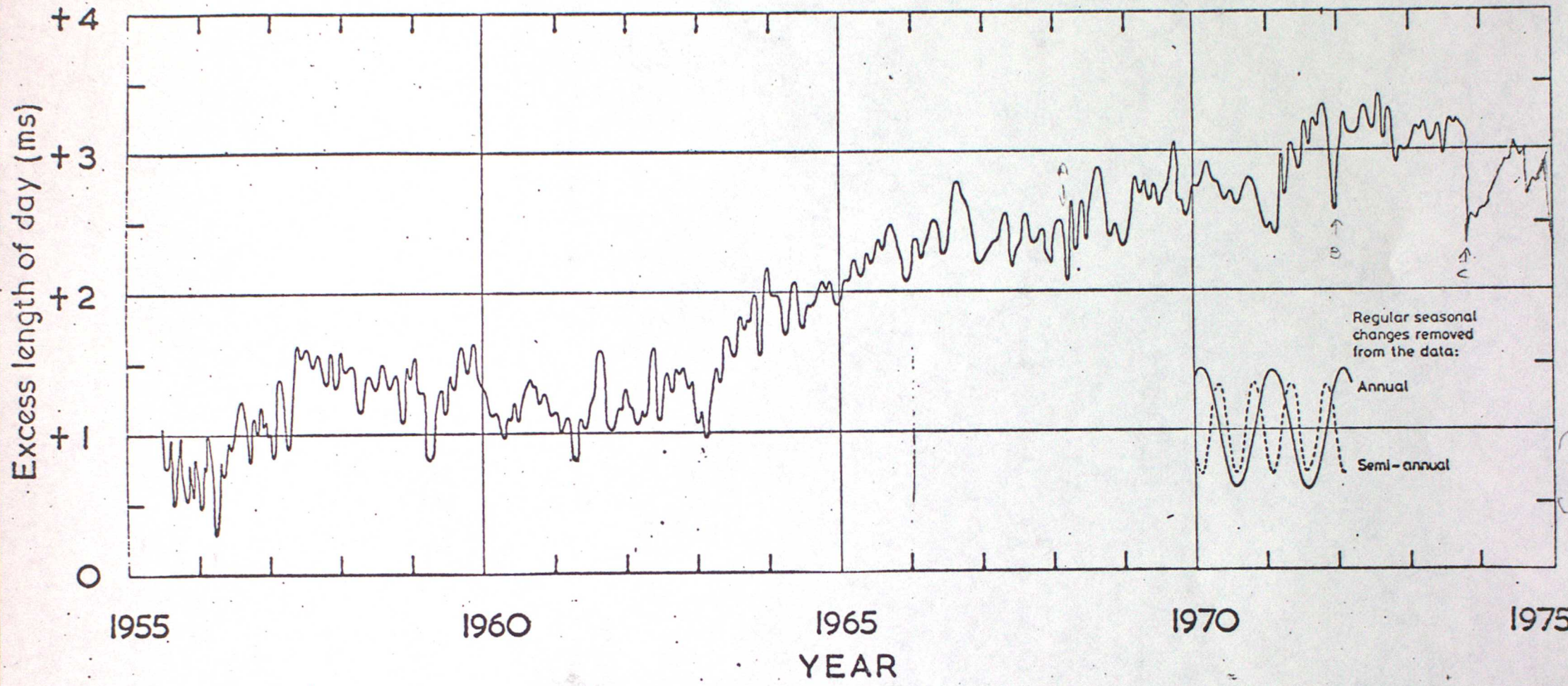

Fig. 2.1 Irregular fluctuations in the rate of rotation of the Earth, in units of the excess length of the day compared with the atomic day of 86400 seconds, derived from BIH data for TAI - UT1. The periodic seasonal variations shown in the caption have been removed from the data. A, B and C are periods considered

Figure 5.1 Pressure Anomaly Fields over N. America during L.o.D. Decrease. Dec 7-11 1971

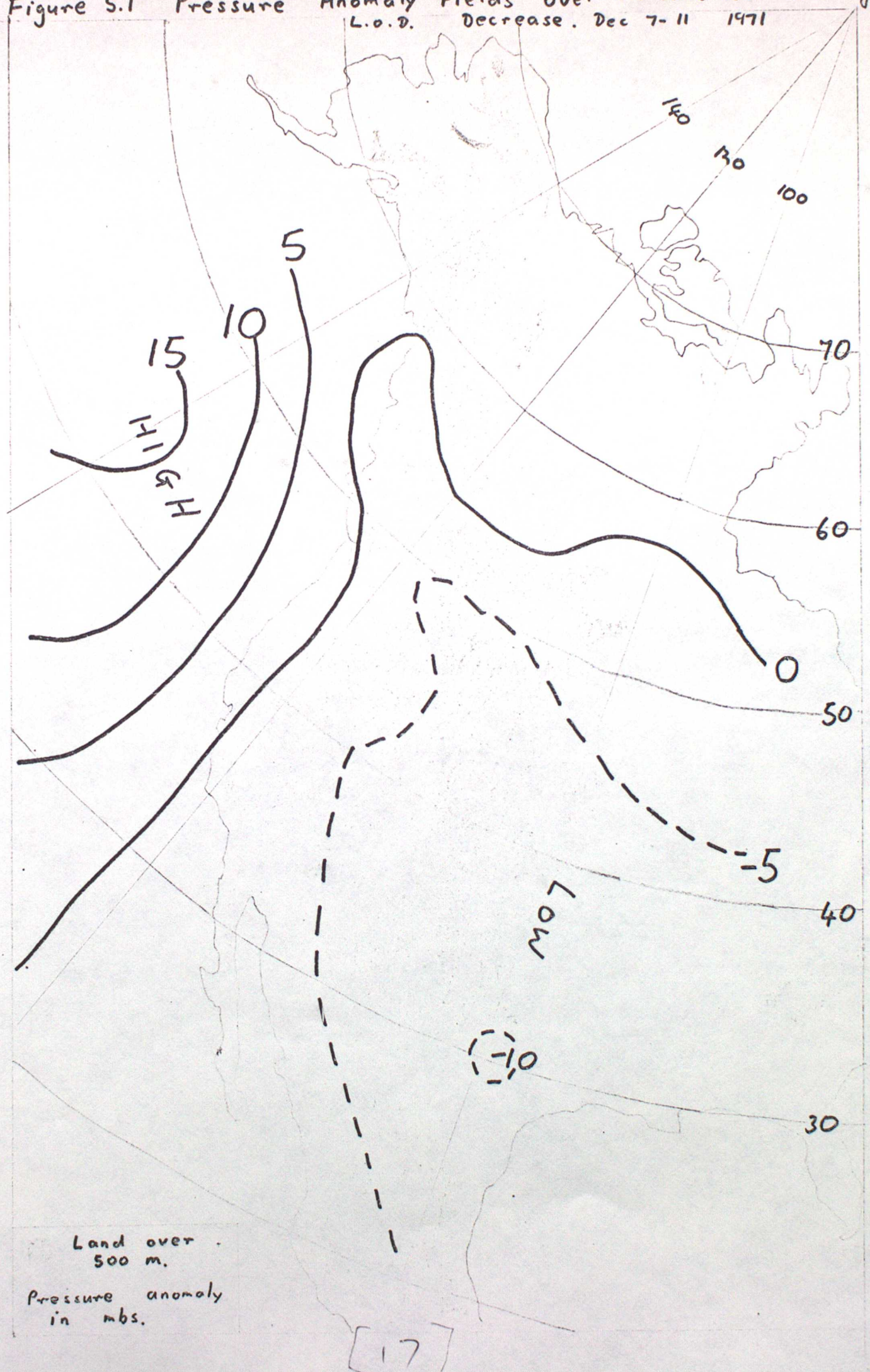

Figure 5.2 Pressure Anomaly Fields over N. America during L.o.d. decrease. Dec 22-26 1973

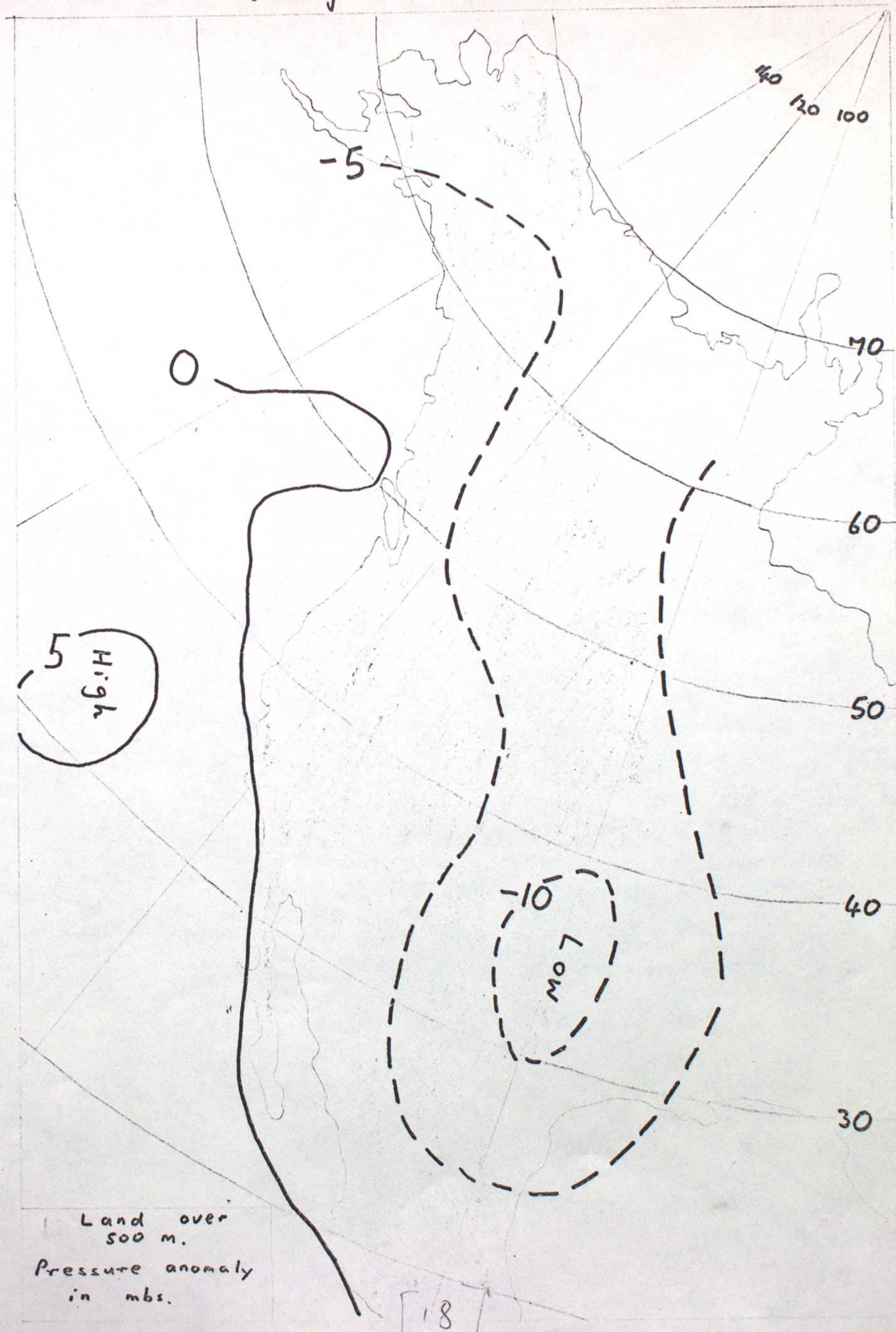
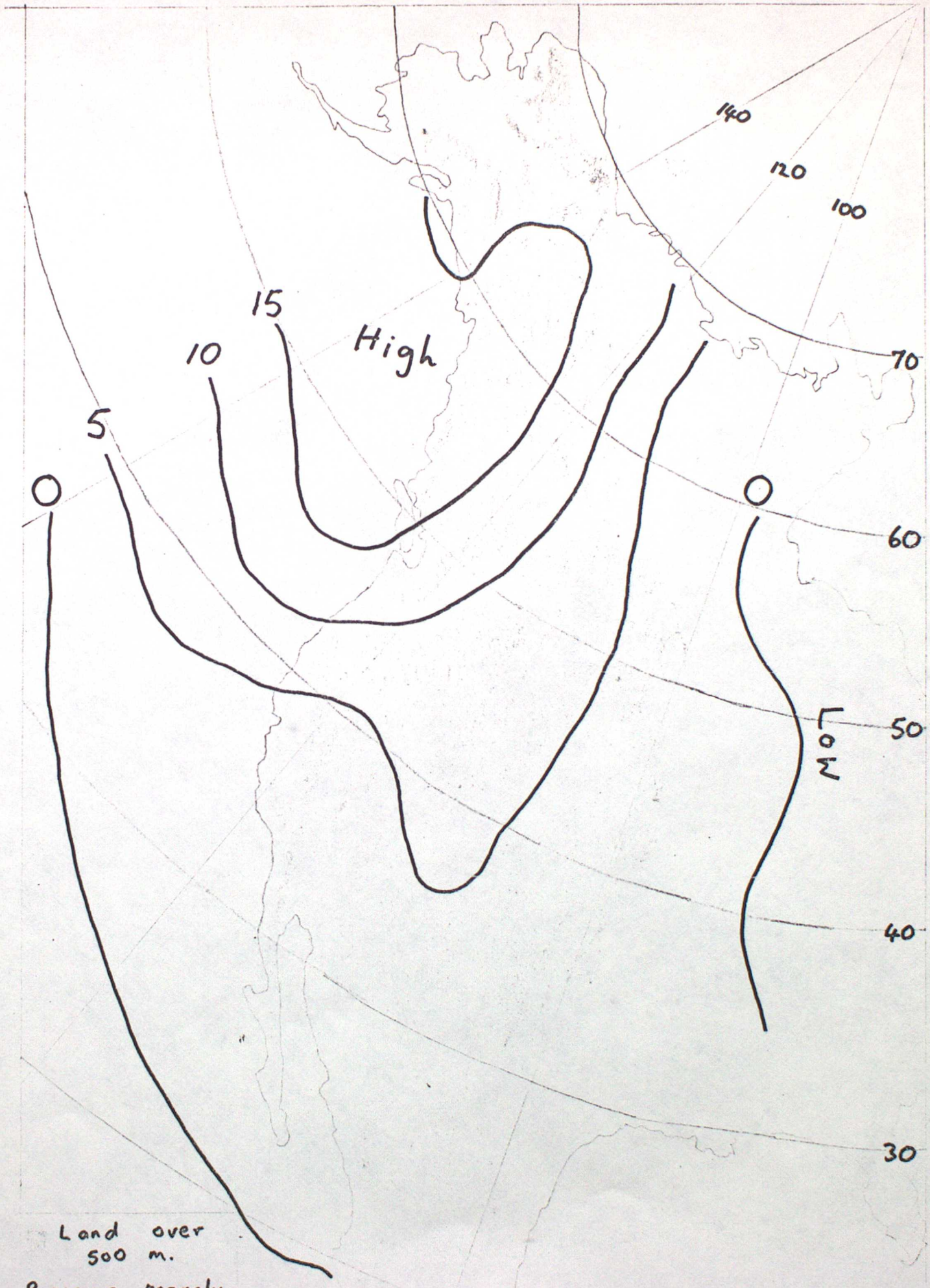
Figure 5.3 Pressure Anomaly over N. America during L.o.D. Increase. MAR 17-21 1971